

FLOW IN AN UNDERFLOOR PLENUM

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ABSTRACT

We describe the flow in an underfloor plenum. We show that the geometry of the plenum causes the flow to exhibit two-dimensional dynamics and to develop flow patterns that are determined by the inlets of the underfloor into the plenum void. We describe laboratory experiments that simulate these flows and also show that the location and number of diffusers in the plenum has little effect on the underfloor flow. Depending on the location of the inlets to the plenum, the flow can exhibit complex vortex patterns and may be time dependent. The presence of these vortices produces different residence times of the air in the plenum. Consequently, the heat transfer through the flow from the room above can lead to significant spatial and temporal variation of the air entering the room through different diffusers.

INTRODUCTION

In an underfloor air distribution (UFAD) system conditioned air is fed into a space through diffusers set into a raised floor. The conditioned air is supplied to the plenum beneath the raised floor. Measurements in a building by Bauman (2004), reproduced in figure 1, show that there can be significant temperature variations in the air underneath the plenum.

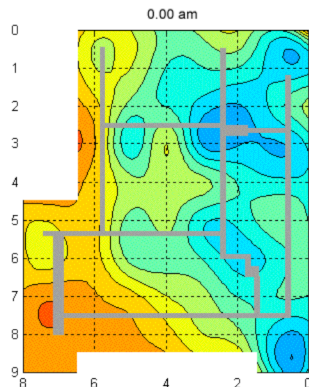


Fig.1. Temperature distribution in an underfloor plenum; from Bauman (2004).

When conditioned air enters the plenum it is heated by transfer of heat through the floor from the warmer space above. Thus, these temperature variations result from the unequal residence times of the air in the plenum before it enters the room through a diffuser. These differences in residence times result from the different trajectories the air takes from the inlets to the plenum to the diffusers. Attempts have been made, by adding air ‘superhighways’ and other duct work, to distribute the air evenly in the plenum. However, this approach is empirical and has not led to general principles for optimizing the design.

This paper describes laboratory experiments that simulate the flow within the plenum and allow the flow patterns to be observed and related to the inlet and diffuser configurations. We show that the flow patterns are set by the locations of the inlet and the geometry of the floor plate, and is independent of the location of the diffusers.

THEORY

The flow in an underfloor plenum is governed by two-dimensional dynamics. Since a typical plenum is about 0.3m deep and can be up to 15m across, the geometry forces the air to flow horizontally under the plenum before it enters the space through the diffusers. Let L represent the horizontal scale of the plenum and h its depth. Then the continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0,$$

implies that the scale W of the vertical velocity w is related to the scale U of the horizontal velocity u by

$W \approx \epsilon U$, where $\epsilon = \frac{h}{L} \ll 1$ is the aspect ratio of the plenum.

Thus vertical velocities are very small compared to the horizontal flows except in the immediate neighbourhood of the diffusers. Thus the flow can be

represented by a streamfunction $\psi(x, y)$, where x and y are the horizontal coordinates. In the absence of friction and time-dependence, the stream function satisfies

$$\nabla^2 \psi = f(\psi), \quad (1)$$

where ∇^2 is the horizontal Laplacian and f is any function. The case where f is chosen to be a linear function of ψ was discussed in Kanda & Linden (2001). In that case

$$\nabla^2 \psi = \lambda \psi, \quad (2)$$

where λ is a constant. It was found that flows governed by (2) were determined by the geometrical arrangement of the forcing, which correspond to the locations of the inlets of the conditioned air to the plenum. Examples of flow patterns obtained as solutions to the Helmholtz equation (2) for different values of the eigenvalue λ are shown in figure 2.

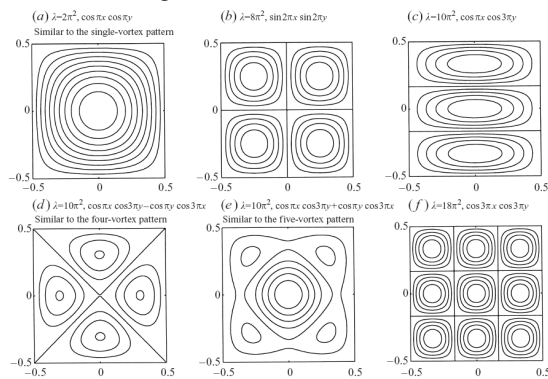


Fig. 2 Flow patterns for planar flow for different forcing arrangements found as resonant modes of the Helmholtz equation (2).

Experiments were conducted on planar flows in a stratified fluid Kanda & Linden (2001) in which the flow was forced by supplying fluid at a discrete set of sources and removed at a discrete set of sinks. In this arrangement the sources are equivalent to the supply inlets to the plenum and the sinks represent the cooling diffusers that extract air from the plenum. The role of the stratification is to reduce the vertical velocity and generate a planar flow. In these stratified experiments it was observed that the flow patterns shown in figure 2 could be observed depending on the location of the sources. It was also found that the flow patterns were independent of the location of the sinks from which fluid is removed. Since these sinks represent the diffusers, it seems likely that in the plenum flow their positioning is of secondary importance. The aim of the present experiments is to carry out experiments with a model plenum, in which the flow is constrained by the geometry of the plenum rather than the stratification, to see whether the conclusions found by Kanda & Linden

(2001) for the stratified planar flow apply in that case also.

RESULTS

(a) Effect of supply configuration

Figures 4 and 5 show the flow patterns in the plenum for 4 supply inlets. In figure 4 the inlets are located at the corners of the plenum, while in figure 5 they are at the mid-points of the sides. Both cases show significant vortex motion and complex flow paths. The flow in figure 4 is close to that in figure 2(d) and that in figure 5 is similar to that in figure 2(b). Since they correspond to these theoretically predicted flows, it suggests that these plenum flows are governed by two-dimensional dynamics and, therefore, the same conclusions apply to them. This conclusion is also supported by the observation that the particle paths shown in figures 4 and 5 generally do not cross over one another. Side view observation of the flows also showed that the motion was primarily horizontal.

Similarly, the *vertical* location of the supply vents within the plenum plays little, if any, role. Figure 6 shows the same source arrangement as in figure 4, but with the supply nozzles placed directly on the slab below the plenum rather than at mid height. The similarity between the two flow patterns confirms that the flow is essentially two-dimensional.



Fig. 4. The flow pattern for supply inlets in the corners of the plenum.

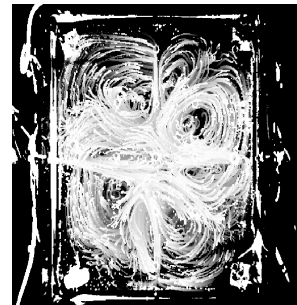


Fig.5. The flow pattern for supply inlets at the mid-points of the plenum sides.



Fig. 6 The same supply arrangement as in figure 4 except that the inlets to the plenum are located adjacent to the slab rather than at mid depth.

(b) Effect of diffuser location

A second feature of these flows is that the differences are caused primarily by moving the locations of the inlets, and the location of the diffusers has little effect on the flow patterns. Figure 7 shows the diffuser geometry. In most experiments all the diffusers were open, but cases were run with the inner or outer 8 diffusers closed as shown in figure 7. Three examples of the flow are shown in figure 8.

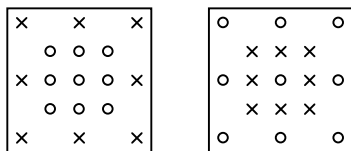
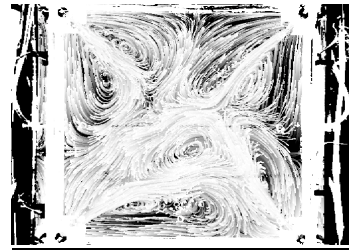


Figure 7 shows the arrangements of open (circles) and closed (crosses) diffusers.

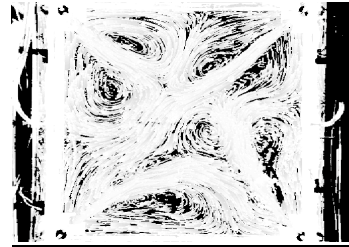
In figure 8(a) all 17 diffusers are open, while in 8(b) the outer 8 diffusers are closed and in 8(c) the inner 8 diffusers are closed. As can be seen in the figures there is no significant difference in the flow patterns. Thus the main aspect that controls the circulation under the floor is the horizontal location of the supply inlets to the plenum. Opening or closing diffusers during operation has little effect on this flow distribution.



(a)



(b)



(c)

Fig. 8. Flow patterns with the same inlet conditions. In (a) all 17 diffusers are open, while in (b) the outer 8 are closed and in (c) the inner 8 are closed.

(c) Other flow patterns

Figures 9 and 10 show further flow patterns generated by different locations of the supply inlets. Figure 9 shows the effect of locating all the inlets at one end in an attempt to generate a uniform flow along the plenum. As can be seen the flow develops into 3 large vortices and, at least for these flow speeds, does not penetrate to the far end of the plenum. This example also illustrates a feature that is observed in all the experiments – that the scale of the vortices is set by the domain size and the number of inlets.

Figure 10 shows the case where the two inlets are in opposite corners and are directed towards each other. The flow shows a predominantly two-vortex pattern.



Fig. 9 The flow generated by 3 inlets at one end of the plenum.



Fig. 10 The flow generated by opposing inlets on two sides of the plenum.

(d) Effect of plenum depth

Experiments were run at three different plenum depths, 1.0, 1.5 and 2.0 cm, so that $\varepsilon = 0.017, 0.025$ and 0.034 , respectively. In each case $\varepsilon \ll 1$; a typical open plan space has $\varepsilon \approx 0.02$. We found that for $\varepsilon = 0.017$, the flow developed a steady pattern in a relatively short time. On the other hand for the deepest plenum ($\varepsilon = 0.034$) the flow remained unsteady and did not form a regular pattern. The time to reach a steady state increased with the plenum depth and suggests that the geometric constraint is important in achieving a two-dimensional flow.

DISCUSSION

These results show that the flow in an underfloor plenum is essentially two-dimensional. Consequently, it is governed by a Helmholtz equation for the streamfunction and forms vortex patterns that are determined by placement of the air supply inlets to the plenum. These flows are exact analogues to planar flows in a stratified fluid studied by Kanda & Linden (2001).

Kanda & Linden (2001) showed that certain rules govern the formation of these vortex patterns. Of particular interest here is the possibility of forming a single, large-scale vortex as shown in figure 11.

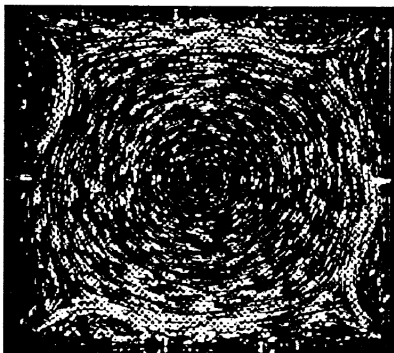


Fig. 11 A single large-scale vortex pattern.

This flow configuration has the advantage that the inlet flow is directed around the perimeter of the plenum and slowly penetrates into the centre. Consequently, the residence time for diffusers near the perimeter of the space is shorter than that for diffusers in the interior. As

a result the air to the perimeter diffusers is cooler than that to the interior. For circumstances when extra cooling is needed near the perimeter this flow pattern seems to be optimal.

The basic rule determined by Kanda & Linden (2001) is that the large scale circulation requires that the flow from the inlets be directed towards the centre of the domain. In that case all the jets meet at the central point and they interact in such a way as to produce this steady large-scale circulation. This is the case for the flow shown in figure 4 and, while it is not as simple as that shown in figure 11, there is a predominant central circulation. Some of the differences result from the lower velocities from the outlets in the flow shown in figure 11, which leads to a more regular flow pattern.

On the other hand if the inlet flows are not directed towards the centre, the flow tends to form smaller vortices that are more irregular and in some cases unsteady.

A second important result of these experiments is that the location and number of the open diffusers has little effect on the flow patterns in the plenum. Consequently, the UFAD system is quite flexible in that diffusers may be opened or closed without significant impact on the plenum flow.

We also note that the vertical location of the inlets within the plenum is not important – nor indeed is their cross-sectional area. The flow patterns are governed solely by the horizontal location and directions of the outlets.

On the other hand the depth of the plenum did affect the flow. For small aspect ratios a regular pattern developed quickly and was consistent with two-dimensional dynamics. For the deeper plenums the approach to steady state was slower, and for the deepest case, the flow remained unsteady. Since our smallest depth corresponds to a plenum 30cm deep with a floor plate of 15m length, this result suggests that care must be taken when sizing the plenum void in a building.

As shown in figure 1, temperature variations may be several degrees Celsius. The effect of these variations is likely to result in complicated room stratification profiles. The impact of this variability on the efficiency and comfort of a UFAD system requires further study.

REFERENCES

- Bauman, F. 2004 Personal communication
- Kanda, I. & Linden, P.F. 2001 Sensitivity of horizontal flows to forcing geometry. *J. Fluid Mech.*, **432**, 1-23.

